Comparison of temporal evolution of the EUV emission in gadolinium and tin laser-produced plasmas

Imam Kambali*, Tony Donnelly, Enda Scally, Gerry O'Sullivan, Padraig Dunne and Fergal O'Reilly

School of Physics, University College Dublin, Dublin 4, Ireland

A modified ISAN spectrometer, with approximately 1 ns resolution, in the wavelength range 5 nm to 60 nm has performed time-resolved spectroscopic measurements of gadolinium and tin laser-produced plasmas. The plasmas were produced at power densities of 5.2×10^{11} W/cm² and 5.5×10^{12} W/cm² with laser spot diameters of approximately 140 μm and 40 μm respectively. The Sn plasma emits at > 50% max. intensity for approximately 9 ns whereas the Gd plasma emits at > 50% max intensity for approximately 2.5 ns.

1. Introduction

Previous studies have shown that strong unresolved-transition arrays (UTA) in a laser-produced plasma (LPP) of tin (Sn) centered near 13.5 nm offers a promising source of EUV radiation for the next generation of lithography in semiconductor industries.

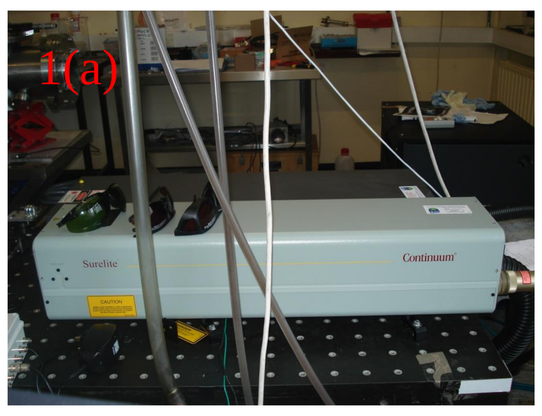
Very recently, Gadolinium (Gd) has been proposed as a future shorter wavelength source of EUV light as its UTA peaks around 6.7 nm and its spectral behavior depends on the laser power density as well as viewing angle [1] .

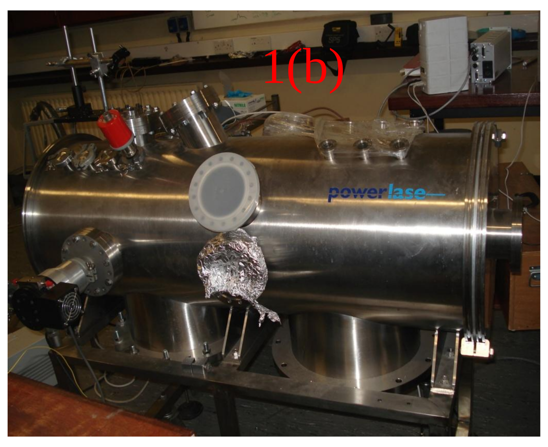
Better understanding of the Gd and Sn plasma behavior over time is one of the keys to successfully producing optimised radiation sources.

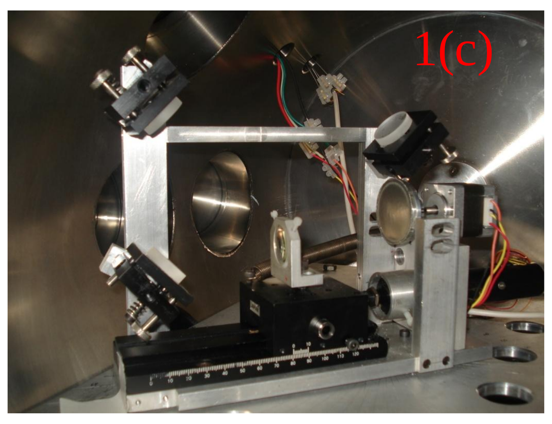
2. Experimental set up

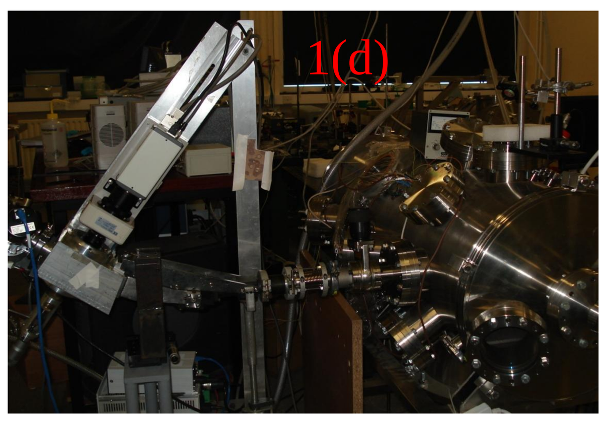
The experimental set up consists of:

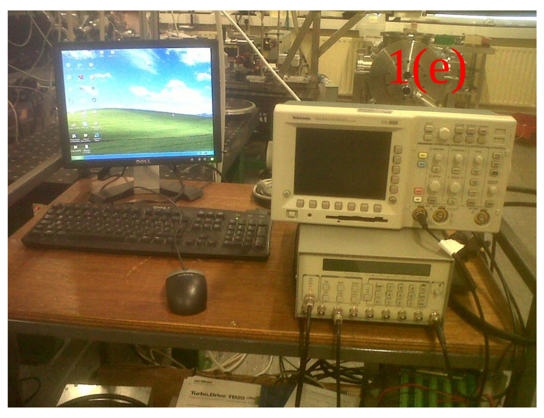
- Nd:YAG laser, 7 ns FWHM, 50 Hz, Energy up to 530 mJ (Fig. 1(a)).
- Vacuum chamber which was evacuated down to 5×10^{-6} mbar (Fig. 1(b)).
- Target system where Gd (99.99% purity) and Sn (99.95% purity) are placed on (Fig. 1(c)).
- Modified ISAN spectrometer with spectral range from 5 nm to 60 nm depending on the grating as well as phosphor size employed (Fig. 1(d)).
- Hamamatsu digital ICCD camera with fast gating to a minimum of 250 ps (Fig. 1(d)).
- Stanford digital delay/pulse generator (model DG535), oscilloscope, as well as data acquisition system (Fig. 1(e).
- A fast-response phosphor made from p-Terphenyl (fig. 1(f)) which has decay time of around 1 ns [2] is used to capture the Gd and Sn EUV emission.

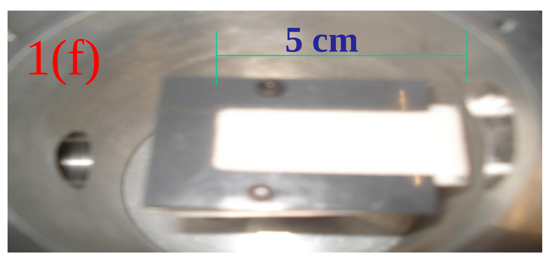












3. Results

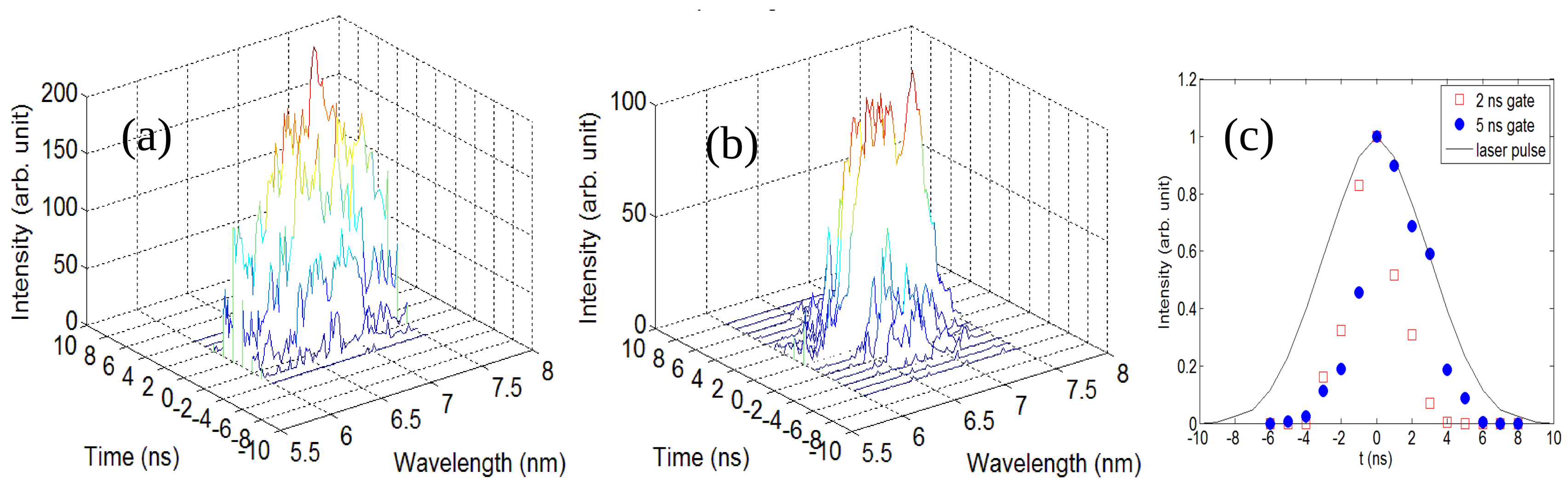


Fig. 2 *Temporal evolution of gadolinium spectra at Φ = 5.2×10^{11} W/cm² (spot diameter of 140 μm), gated for (a) 2 ns and (b) 5 ns windows. The in-band intensity over 6.7 nm ± 0.6% bandwidth for each time gate is shown in (c).*

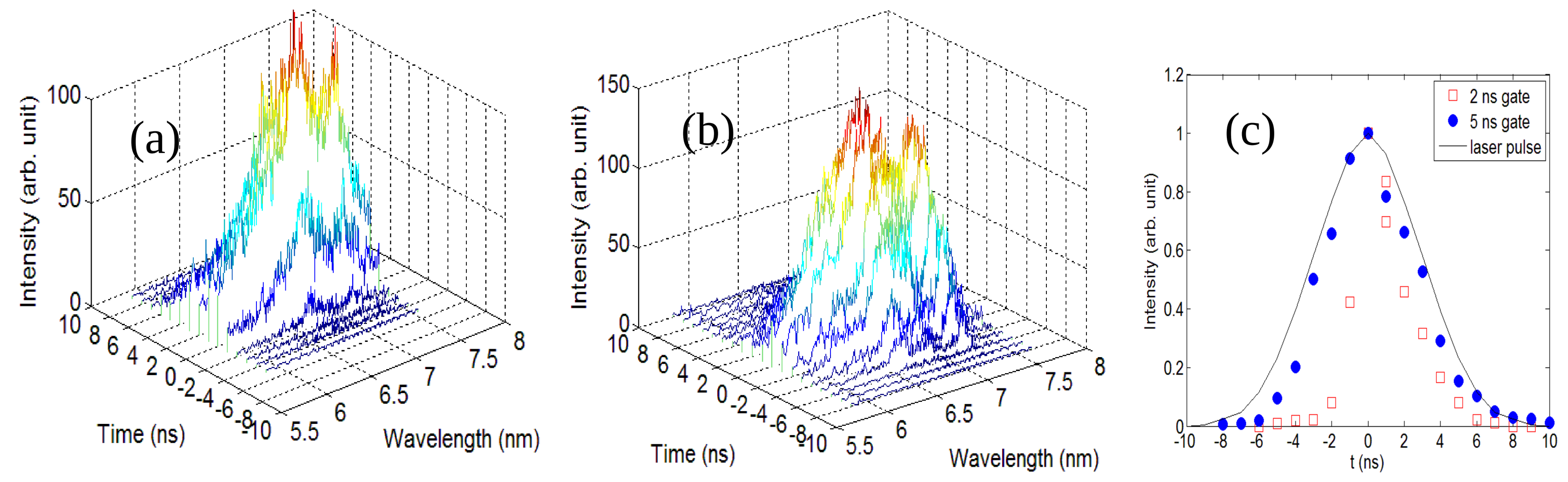


Fig. 3 *Temporal evolution of gadolinium spectra at Φ = 5.5×10^{12} W/cm² (spot diameter of 40 μm), gated for (a) 2 ns and (b) 5 ns windows. The in-band intensity over 6.7 nm ± 0.6% bandwidth for each time gate is shown in (c).*

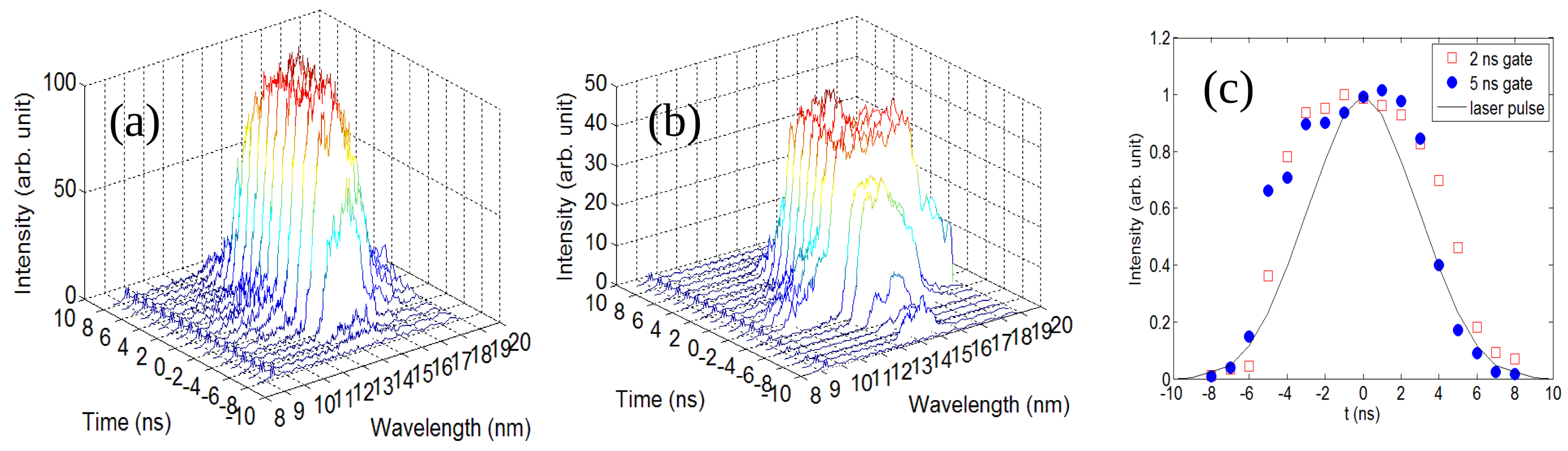


Fig. 4 *Temporal evolution of tin spectra at Φ = 5.2×10^{11} W/cm² (spot diameter of 140 μm), gated for (a) 2 ns and (b) 5 ns windows. The in-band intensity over 13.5 nm ± 2% bandwidth for each time gate is shown in (c).*

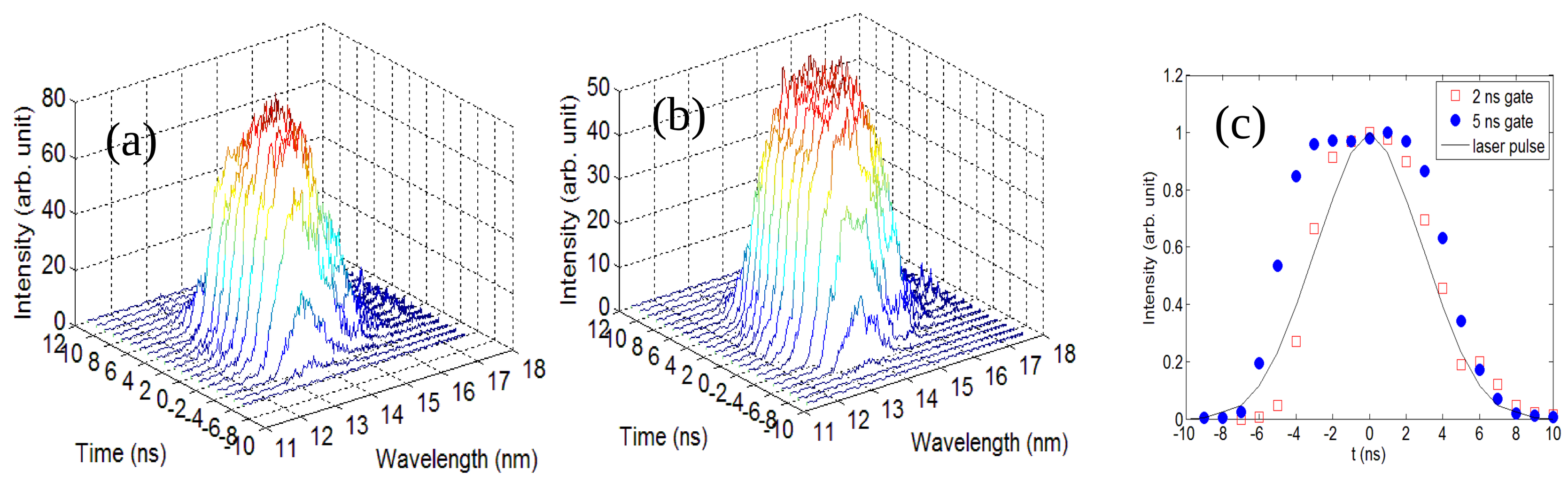


Fig. 5 *Temporal evolution of tin spectra at Φ = 5.5×10^{12} W/cm² (spot diameter of 40 μm), gated for (a) 2 ns and (b) 5 ns windows. The in-band intensity over 13.5 nm ± 2% bandwidth for each time gate is shown in (c).*

4. Discussion

In the timing set up, t = 0 ns corresponds to the peak of the laser pulse.

For the first time, we have captured the temporal evolution of the EUV emission in a Gd LPP (figs. 2 and 3).

At Φ = 5.2×10^{11} W/cm² (fig. 2), 2 main features in the Gd spectra peak around 6.7 (associated with EUV emission from Gd^{13+} - Gd^{22+} nm) and 7.2 nm (due to lower ion stages such as Gd^{7+} - Gd^{13+} [3]) whereas in Sn plasma self-absorption features from Sn^{6+} - Sn^{10+} around 13 – 16 nm are more pronounced (fig. 4) as reported previously [4] with the brightest emission around 13.5 nm (primarily due to Sn^{6+} - Sn^{12+}).

At higher irradiance (Φ = 5.5×10^{12} W/cm²), Gd plasmas (fig. 3) attain sufficient electron temperatures to produce higher ion stages which result in the EUV emission peak at around 6.7 nm dominating that at 7.2 nm which can be seen throughout the plasma emission over time. For an Sn target at this power density (fig. 5), self-absorption is less than that of lower irradiance.

In general, Sn 13.5 nm 2% in-band emission lasts longer than Gd 6.7 nm 0.6% in-band emission, with the Sn plasma emitting at over half its maximum intensity for approximately 9 ns (at Φ = 5.2×10^{11} W/cm²) and 7ns (Φ = 5.5×10^{12} W/cm²), whereas the Gd plasma emits at over half its maximum intensity for approximately 2.5 ns at both power densities.

5. Conclusion

For both power density conditions (*Φ = 5.2×10^{11} W/cm²* and *Φ = 5.5×10^{12} W/cm²*), Sn 13.5 nm 2% in-band emission lasts longer than Gd 6.7 nm 0.6% in-band emission. The Gd plasma emitting at over half its maximum intensity for approximately 2.5 ns at both power densities whereas the Sn plasma emits at over half its maximum intensity for approximately 9 ns (at Φ = 5.2×10^{11} W/cm²) and 7ns (Φ = 5.5×10^{12} W/cm²).

References

[1] C. O'Gorman et al., Appl. Phys. Lett. 100, 141108 (2010).
[2] T. A. DeVol, D. K. Wehe and G. F. Knoll, Nucl. Instr. Meth. Phys. Res. A327, 354-362 (1993).
[3] S. S. Churilov, R. R. Kildiyarova, A. N. Ryabtsev and S. V. Sadovsky, Phys. Scr. 80, 045303, (2009).
[4] O. Morris, F. O'Reilly, P. Dunne, and P. Hayden, Appl. Phys. Lett. 92, 231503 (2008).

Future work

1. Improving imaging system to get statistically better results.
2. Varying power density.

Acknowledgements:

This work was supported by Science Foundation Ireland under Principal Investigator grant number 07/IN.1/I1771. Technical assistance by Dave Cooney, Frank Heffernan, Victor Litera, Brian O'Connor and Brian Redmond as well as discussion with Dr. Larissa Juschkin are greatly acknowledged.

***corresponding author: Imam.Kambali@ucdconnect.ie**

UCD DUBLIN

sfi Fondúireacht Eolaíochta Éireann Science Foundation Ireland